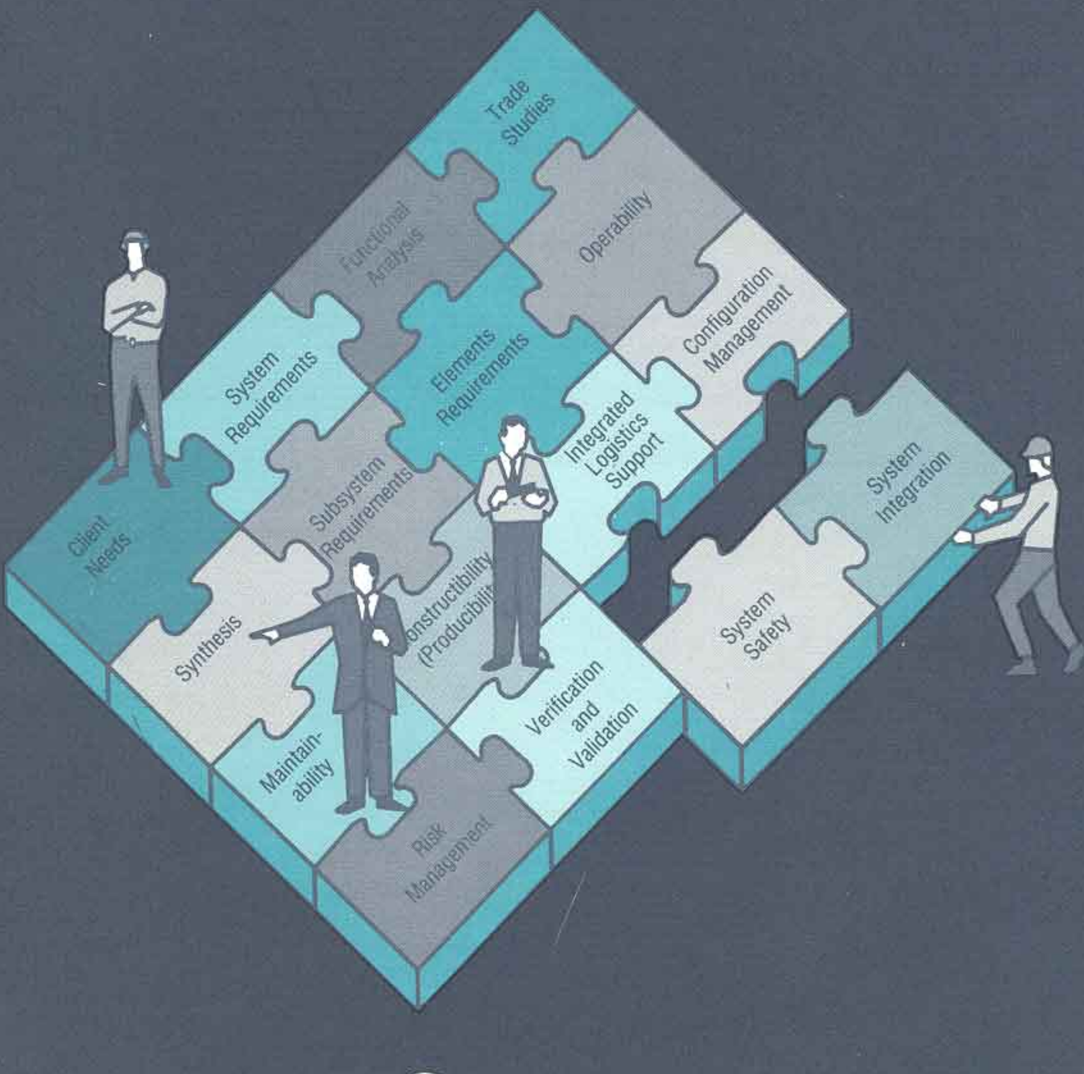
A Guide to the SYSTEMS APPROACH



Bechtel National, Inc.

When we mean to build,
We first survey the plot, then draw the model;
And when we see the figure of the house,
Then must we rate the cost of the erection;
Which, if we find outweighs ability,
What do we then but draw anew the model
In fewer offices, or at least desist
To build at all?

William Shakespeare
King Henry IV, Part 2, Act 1, Scene III

February 1989

In June 1988, BNI formally changed its letterhead to read "Systems Engineers—Constructors." This change highlighted our increasing emphasis on the Systems Approach in relating to complex, technically innovative projects that characterize much of our present workload. It is also the commonly used method applied by aerospace and other high-tech industries in the performance of major systems engineering projects, and is rapidly becoming a requirement on most government work.

This guide had been prepared as an aid to understanding the systems engineering process and its key elements. It incorporates many of the activities we at Bechtel have used for years on our projects. Our goal is to train BNI engineers in the application of the Systems Approach so that we may enhance Bechtel's reputation for being fully responsive to our client's needs.

I place great importance on your developing a thorough understanding of the Systems Approach and its application to our work. I encourage your active participation and feedback as we expand our use of the Systems Approach.

W L Friend

W. L. Friend
President,
Bechtel National, Inc.

Introduction

Throughout history, man has continuously demonstrated his innate ability for problem solving. From the simplest of yesterday's challenges to the most sophisticated posed by today's high technology, the basic approach of finding acceptable solutions to determined needs has been used.

In tackling these challenges, man has also had to solve the problem of managing increasingly complex systems. By the late 1950s, the complexity of building nuclear powered ships and generating stations, high performance aircraft, and space systems had led to the development of several sophisticated management techniques. These techniques focused on the interactions of many elements working in harmony to achieve the desired effect.

The elements together were called systems, and the process of achieving the harmonious integration was called Systems Engineering. The key to the process was, and still is, a disciplined approach to solving engineering problems.

Bechtel has been an active player in solving many of man's more challenging engineering problems, from bridges and dams to nuclear power plants and environmental cleanup. Along the way, Bechtel has developed and implemented many of the elements of Systems Engineering. This has been especially true within Bechtel National, Inc. (BNI) where client requirements have placed a heavy emphasis on integrating complex, technologically innovative systems.

As a member of the BNI team, you are a key player in our Systems Engineering process. Your contribution is essential to the ultimate success of our systems solutions to clients' needs.

This guide was developed to aid in your understanding of the Systems Engineering process and its key elements. Hopefully it will serve to stimulate your interest in becoming a proactive participant in the Systems Engineering process.

The main text provides a concise overview of:

- The Systems Approach
- Systems Engineering management

The Systems Approach

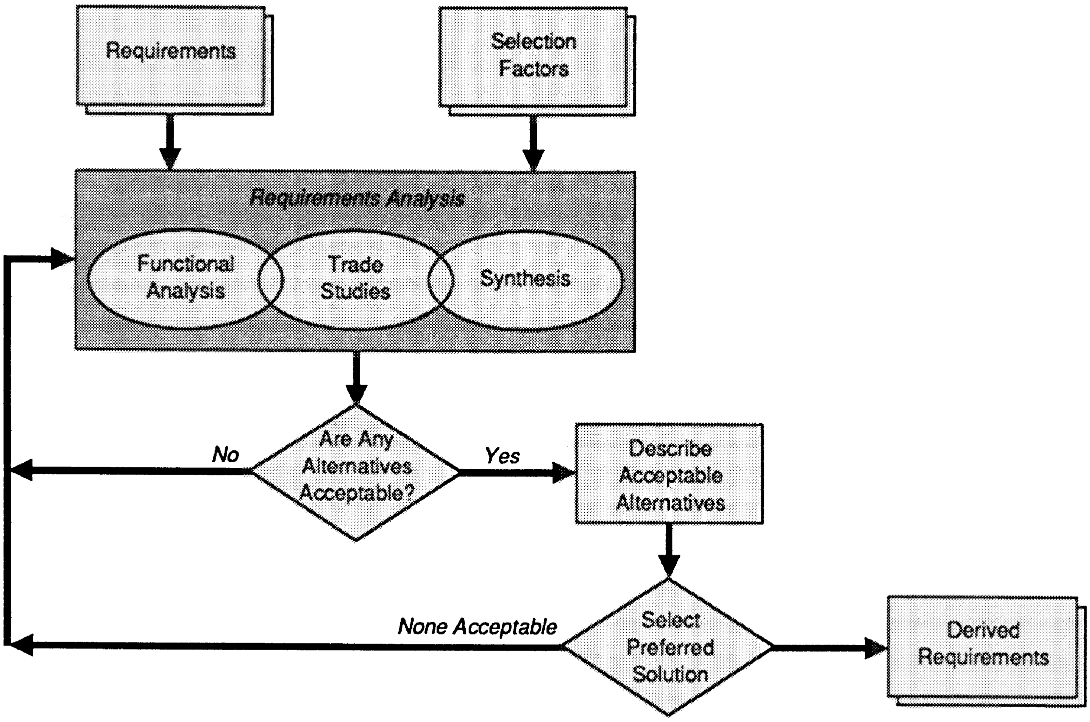
The Systems Approach focuses on understanding the client's requirements throughout a system's life cycle, which includes the following phases:

- During the initial concept development, the Systems Approach is applied to define the basic requirements and a preliminary configuration for the system.
- In the design process, the initial definition is iterated into requirements and configurations for subsystems and elements; simulation and prototyping are used selectively to verify that harmony will be achieved for the total system.
- The construction, manufacturing, and startup phase translates the detailed requirements and configurations into discrete items and combines them into subsystems and systems; checks are performed continually to assure requirements are fulfilled. The results of the checks are used in the ongoing systems process to make adjustments when necessary and to assure that the client's total system needs will be satisfied.
- The Systems Approach continues in the operations and maintenance phase with emphasis on sustaining the system's usefulness and, when desired, making enhancements beneficial to the client's needs.
- Eventually a system completely fulfills its purpose and is decommissioned; the Systems Approach is applied to aid the client in realizing any scrap or reuse value, making the deactivation environmentally beneficial, and garnering valuable lessons learned to be applied to future systems.

Throughout the system's life cycle, the Systems Approach is used to achieve and sustain harmony among the elements of the system. To achieve this, all the requirements, especially the relative importance among the requirements, must be known.

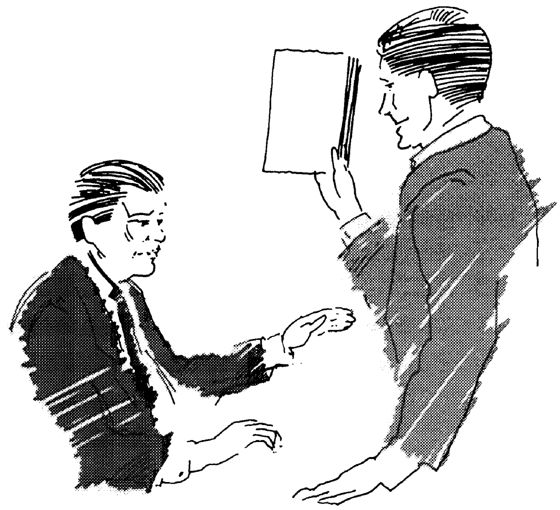
Figure 1 represents the basic process used in the Systems Approach.

Figure 1 The Systems Approach Requires an Iterative Process



Note that requirements appear at both the beginning and the end of the process. The input requirements, along with the selection factors, follow you throughout the process of searching out an acceptable solution. Often, you will iterate through the process several times to assure that all the requirements, along with an acceptable solution, have been found. As you step through the process, your knowledge expands and the completeness of your solution increases. Eventually, you are able to derive and state all the requirements in such a manner that you are ready for implementation.

To help understand the process, let's follow one of our more successful engineers, T. J. Good, as he steps through it.



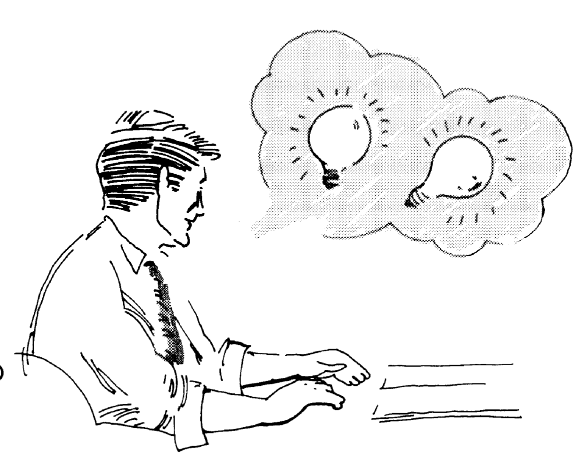
T. J. Good begins by obtaining the client's **requirements and selection factors,** plus any ideas about constraints. To this, he adds other pertinent information like codes, laws, and government regulations; lessons learned from similar systems solutions; and any derived requirements applicable to this iteration of the Systems Approach.

Requirements generally address cost, schedule, and performance needs for the system and may include any characteristic or attribute. Selection factors generally address how well a system fulfills the stated needs. The most often used factors are operability, constructibility, reliability, maintainability, human factors, system safety, risk assessment, logistics, and life cycle cost.

Next, T. J. Good performs a **requirements analysis** using interrelated functional analyses, trade studies, and synthesis activities:

- In **functional analysis,** he organizes the requirements into logical sets. Using requirements allocation trees and functional diagrams, T. J. documents the requirements in related groups. He also identifies constraints and refines selection factors.

- T. J.'s **trade studies** begin with the identification and rough description of feasible technology alternatives. Being careful to avoid value judgments initially, he collects all alternatives and develops enough information about each to support objective comparisons. Then, using the requirements and selection factors, he searches through the alternatives for the combinations of attributes most likely to fulfill the client's system needs.



- ☐ Having discovered some promising ideas, T. J. Good does a **synthesis** of each alternative. He documents each alternative, being careful to objectively describe its attributes. He strives to define each attribute in terms relevant to the requirements and selection factors.

During the functional analyses, trade studies, and syntheses, T. J., like you, expects some overlap and repetition. In fact, he wants it, because of the completeness it produces in the end product.

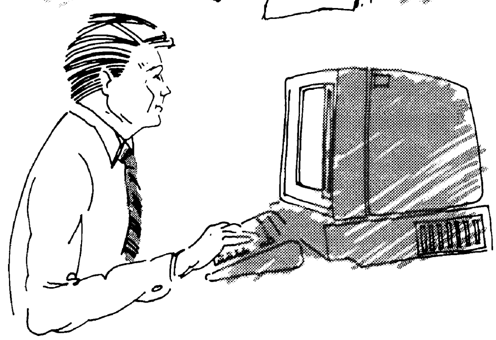
T. J. Good is now ready to objectively determine, **Are any alternatives acceptable?** To find out, he performs trade studies to determine the effectiveness of the alternatives in satisfying the requirements. He scores each alternative's attributes relevant to the requirements and selection factors. Next, he applies weight to the scores based on the relative importance among the requirements and selection factors. After summing the weighted scores and assuring that no single attribute's score far outweighs the bottom line, T. J. has his answer.

Given that at least one, and preferably two or more, alternatives have acceptable scores, T. J. Good will proceed. If not, he returns to the requirements analysis process to further define the requirements and search for alternatives.

T. J.'s **description of the acceptable alternatives** takes the form of a decision package which may include specifications, drawings, and summaries for the alternatives. He begins by summarizing the requirements and selection factors, arrayed in order of importance. He documents each alternative, describing its attributes relevant to the requirements and selection factors, plus its weighted scores.

To help identify a preferred alternative, he summarizes the weighted scores and identifies any significant sensitivity in the scores based on variations in requirements, selection factors, their relative importance, or in the attributes of the alternative. Finally, he states his recommendation and reasons for preferring that alternative.

To **select a preferred solution,** T. J. Good submits his work to the appropriate decision-maker. The outcome can be an affirmation of an alternative, with or without adjustments, or a decision to reiterate based on new ideas or on adjustments in requirements or selection factors.



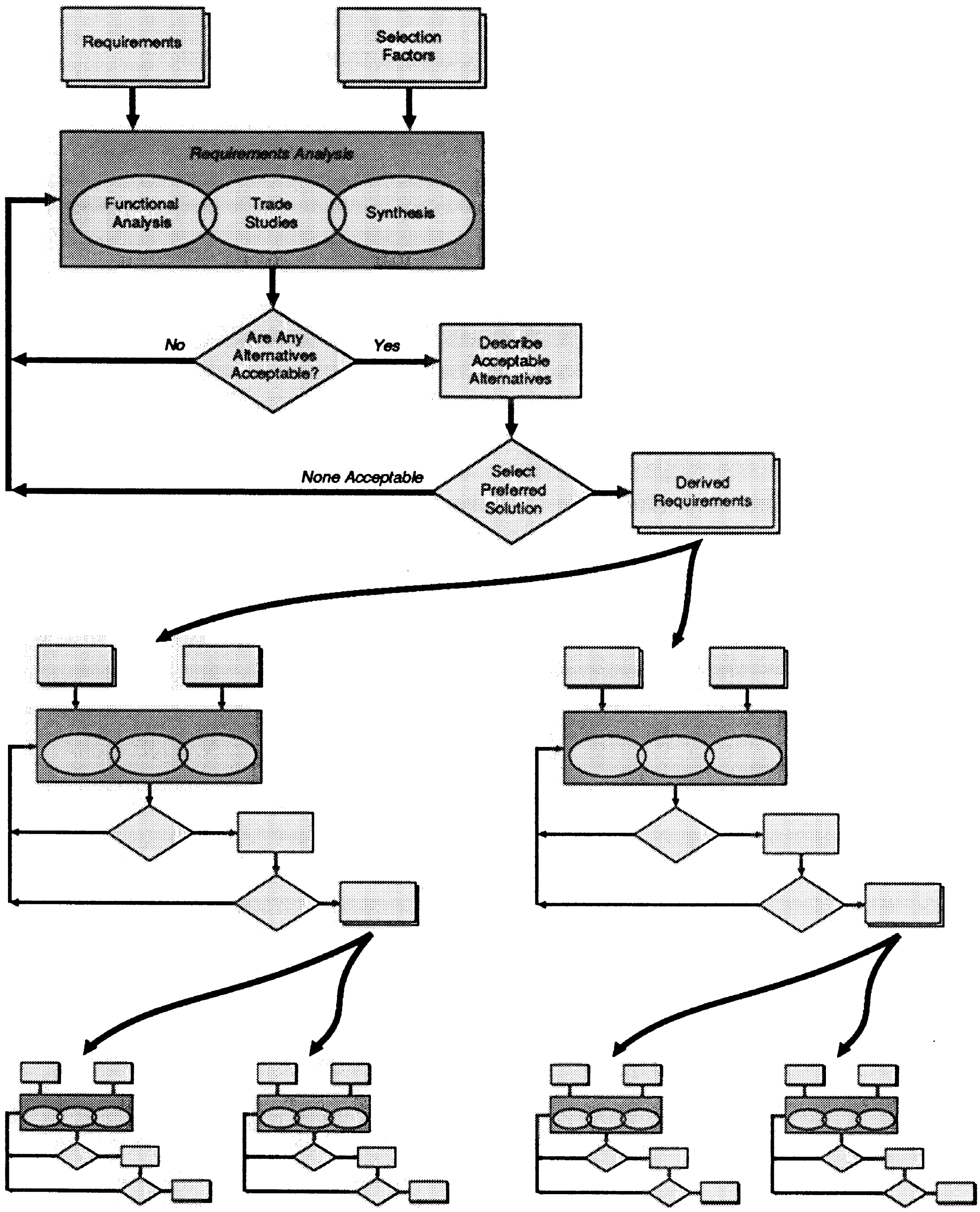
When a preferred solution is selected, T. J.'s final step is to document the **derived requirements.** Using the specifications and drawings developed to describe the alternative, he makes adjustments according to the decision-maker's instructions and completes the documents in a form ready for implementation.

Implementation can take many forms. If T. J. Good's efforts were early in the concept definition phase, the next step could be applying the derived requirements to define subsystems or elements. If he were in the design and development phase, the next step could be buying elements for delivery to the construction site, or an iteration to correct a failure found through simulation.

The Systems Approach will be applied almost continuously during the early phases of a system's life cycle. Figure 2 portrays the flow-down process of understanding the requirements and selecting a preferred solution at the system level, and then allocating to subsystems and elements.

As your understanding and requirements definition expand, the need for integration increases significantly. The techniques for guiding the process and integrating the results, called Systems Engineering management, are described in the next section.

Figure 2 The Flow-Down Process



Systems Engineering Management

Now that T. J. Good, and you, have walked through the Systems Engineering Process, step back and review how this process is managed overall.

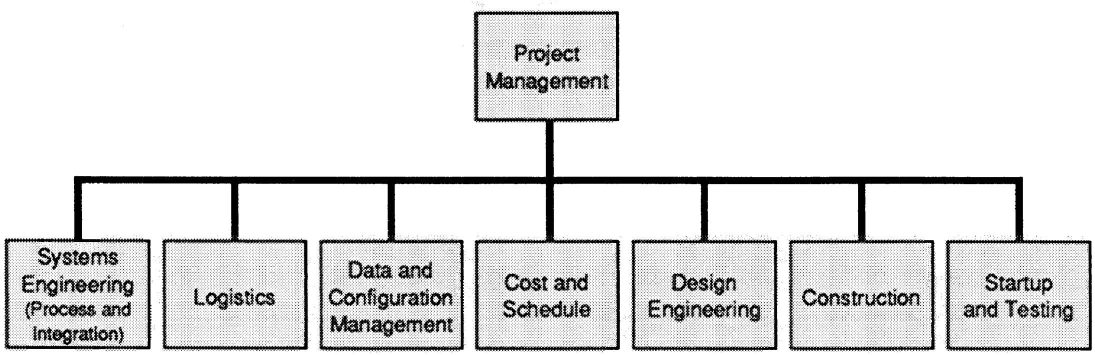
Definitions and Need

Managing the Systems Engineering process encompasses the integration of all engineering activities and technical aspects of the project, from concept through engineering, construction, operation, and decomissioning. It includes the management of the Systems Engineering that is required to:

- Define system performance parameters and preferred system configuration to satisfy the requirement
- Plan and control the technical program tasks
- Integrate the engineering specialties
- Manage a totally integrated effort of design engineering, specialty engineering, test, logistics, production, technical performance measurement, and schedule objectives

Systems Engineering supports all the major functions of project management, as depicted in the simplified project organization chart (Figure 3). Configuration management and logistics support, although part of Systems Engineering, may be treated as organizationally separate on larger projects. Systems Engineering, including configuration management and logistics support, is separate and distinct from Design Engineering.

Figure 3 Typical Project Organization



Planning the Systems Engineering Effort

To properly organize and accomplish all functions required by a specific project, particularly a complex one, Systems Engineering management develops a plan to enhance the process. This top level plan for integrating all system activities provides the mechanism for identifying and assuring the control of the overall engineering process. It generally includes the definition of the fundamental relationships required for engineering specialty integration, which is addressed in more detail later.

The Systems Engineering management plan's purpose is to highlight the organization, direction and control mechanisms, and personnel necessary for attaining cost, performance, and schedule objectives. The who, what, when, where, how, and why of the evaluation and decision-making authority, and relevant interfaces, must be clearly delineated. The level of detail presented in the plan should be appropriate to the system life cycle status and degree of system complexity. Planning of the Systems Engineering management function must be emphasized and should reflect good management judgement with only essential documentation. Considerations of data reporting, retrieval, utilization, and visibility must be thoroughly evaluated. The plan may also contain a detailed description of the specific Systems Engineering process to be used, including specific tailoring to system requirements, in-house documentation, tradeoff study methodology, and types of mathematical and/or simulation models to be used for system and cost-effectiveness evaluations.

The plan is a program- or project-specific document, which may use any format that provides all the necessary information. For U. S. Department of Defense (DoD) projects, the plan should generally follow the format defined in MIL-STD-499A, "Engineering Management," which is outlined below:

- Part I, technical program planning and control, derives program requirements and implements the plan through:
  - Technical task planning and control
  - Design reviews
  - Technical performance measurement
  - Interface management
  - Subcontractor technical monitoring
  - Risk management

— Site integration requirements
— Test and evaluation requirements
— Trade study management

□ Part II, Systems Engineering process, derives technical requirements such as:

— Requirements analysis and definitions
— Functional requirements and allocations
— Effectiveness criteria development
— Analyses and trade studies
— Risk assessment
— Specification management
— Instructional system development

□ Part III, engineering specialty integration, integrates and coordinates the specialty areas, which may include:

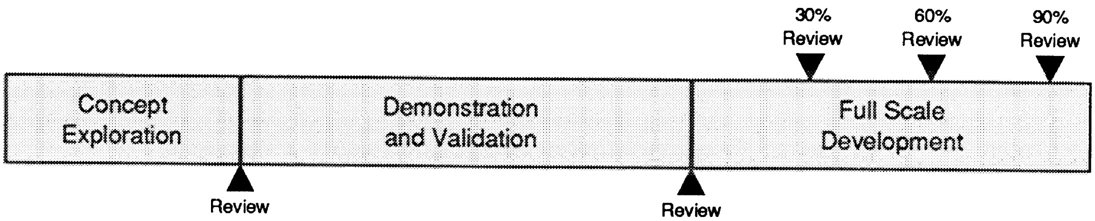
— Reliability
— Maintainability
— Human factors
— Constructibility
— Safety
— Standardization
— Electromagnetic compatibility
— Logistics design interfaces
— Life cycle costs

This three-part breakdown represents one possible method for structuring the plan. Only those items which are basic to the project objectives should be included, along with any other areas unique to the work.

Systems Engineering Management Control Methods

Management control is a basic requirement for all aspects of a project; the level and depth generally vary with the complexity of the work. On typical Bechtel projects, the work is broken down into subsystems and elements, formalized in a project work breakdown structure (WBS). A schedule is developed which establishes key milestones for the project. For each major WBS element a key milestone schedule is developed to form a baseline from which project management may control the work. For example, systems analysis and systems definition could form a major WBS element. A typical milestone schedule for this WBS is shown as Figure 4.

Figure 4   Systems Analysis and Definition Milestone Schedule



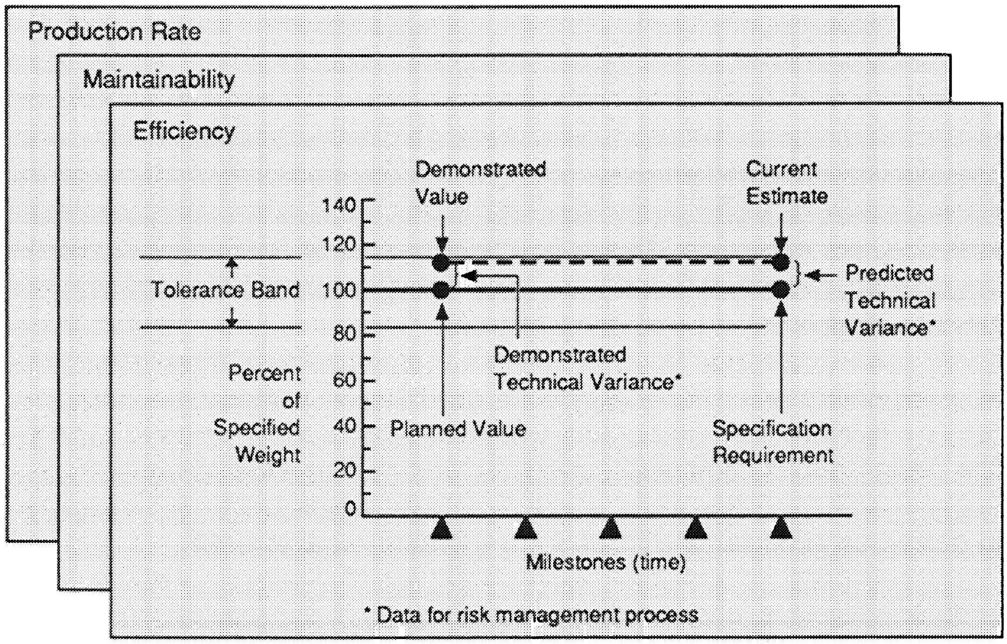
Design reviews play an integral part in the management process and are used to determine the technical adequacy of each element in meeting system and WBS requirements. As the Systems Engineering and design effort proceeds through the life cycle phases, the reviews become more detailed and definitive. Design reviews should include these basic considerations:

- Is the development proceeding toward the objectives in a logical manner?
- Are the design approaches responsive to system performance objectives?
- Is the design an acceptable solution to total system requirements?

As the program develops, and a greater understanding of the requirements and product materialize, technical program reviews can be scheduled to determine if the program is on schedule, or if it should be altered as uncertainties are disclosed, eliminated, or reduced. Most BNI Defense and Space government projects have formal major client technical program reviews scheduled at 30, 60, and 90 percent of design completion. These reviews are a planned part of the Systems Engineering management effort. They are used to seek opportunities for reducing or redirecting the program to optimize budget and time, and for increasing or redirecting program effort to overcome weaknesses in the planned program.

The last major Systems Engineering management control area relates to achieving the technical objectives of the system being evaluated. Called technical performance measurement, and depicted graphically in Figure 5, it is an ongoing, planned evaluation of system performance as measured against specification requirements during the system development process. One typical example, as applied to a high-tech manufacturing plant, would include the technical performance evaluation of robotic equipment. This evaluation might include such parameters as efficiency, maintainability, and production rate, each of which is monitored independently.

Figure 5 Technical Performance Measurement Process

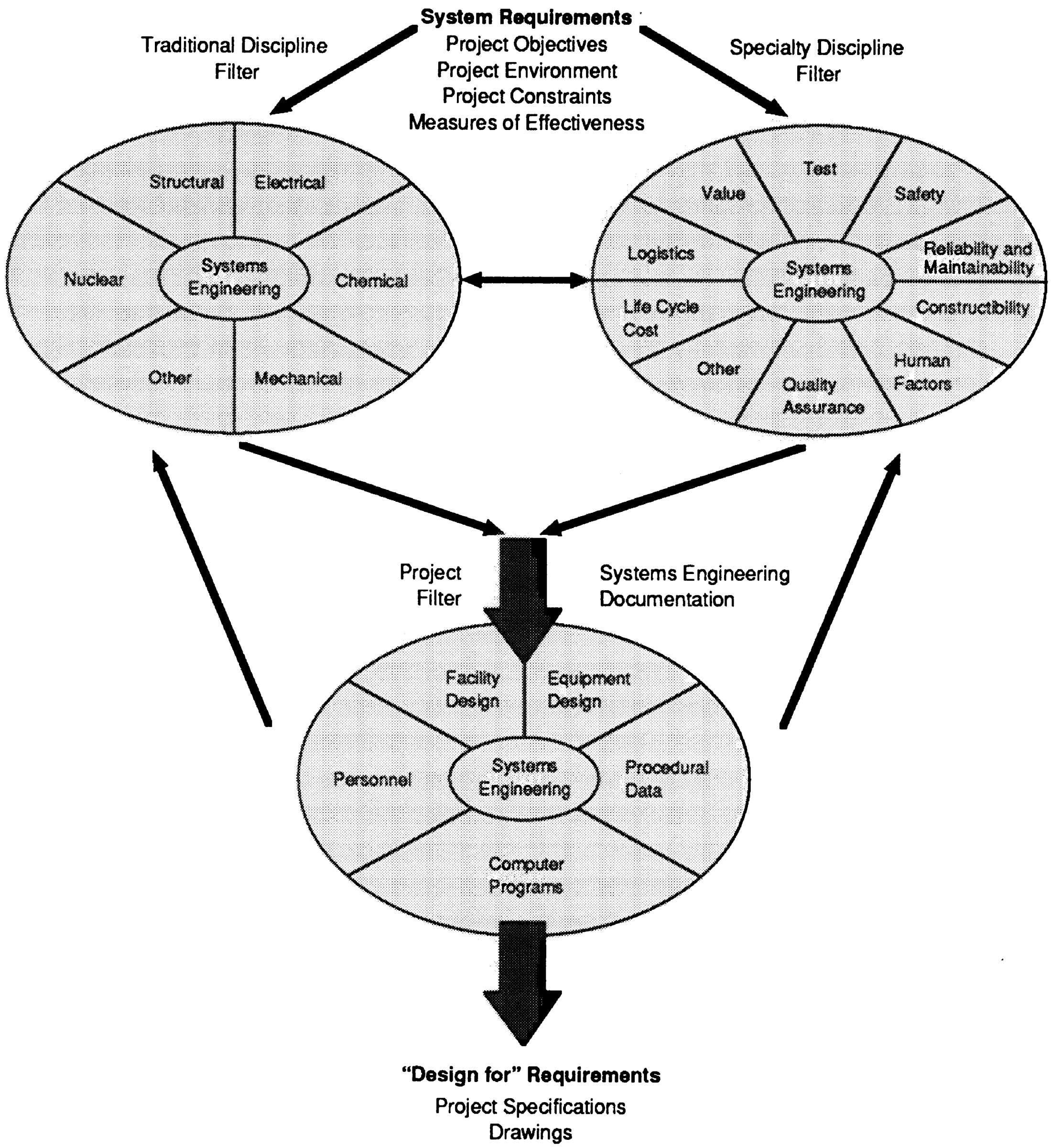


Engineering Specialty Integration

The Systems Engineering approach requires a rigorous technique for integrating design engineering, specialty engineering, and test engineering to ensure their influence on the final design. Particularly, specialty engineering design comes from that portion of the overall engineering effort which is defined by unique specifications and standards relating to each specialty. These constraining specifications often require specific tasks and/or specific data which must be integrated into the overall technical management process.

At any given point in the development process, the design team consists of a mix of traditional, "specialty," test, logistics, and value engineers, and others. At the conceptual phase, the team may consist mostly of operational analysts and traditional engineers skilled in functional analysis. During the design phase, the team's composition shifts to traditional engineers skilled in traditional engineering design practices and specialty engineers skilled in design support. Finally, during construction and activation, the emphasis is focused on a team dominated by construction, logistics, and test engineers. The integration of this iterative process is demonstrated in Figure 6.

Figure 6 Engineering Specialty Integration Process



Three integration "filters" are shown in the overall process. These filters help the engineer to focus on specific aspects of the engineering process. The traditional discipline filter emphasizes those traditional design techniques (such as stress analysis of structures) required at each given stage of the design (conceptual, preliminary, or detailed). Concurrently, design documentation is being developed and/or modified by specialists in areas such as reliability and maintainability. The specialists are establishing some requirements independently of the emerging traditional discipline design, and are also reviewing and modifying the traditional discipline output. Finally, all requirements are filtered by the unique demands of products which comprise the system. The requirements are then described by specifications and drawings, which clearly set out the "design for" requirement.

Although the diagram only depicts a single iteration, for complex projects the process may require many iterations to completely identify and specify all requirements.

Integration of design requirements continues to occur in all phases of the Systems Engineering process. Each discipline filter is integrated within the basic Systems Engineering process steps of requirements analysis (functional analysis, trade studies, and synthesis), evaluation, and decision. All disciplines share common Systems Engineering documentation used to express requirements; this ensures that all specialty disciplines respond to these requirements in a timely, integrated manner.

Summary

Applied throughout a system's life cycle, with greatest emphasis in the early phases, the Systems Approach provides a disciplined method for solving engineering problems.

The methodology focuses on understanding the client's requirements, and integrating all the necessary attributes to achieve a harmonious solution to his total system needs.

The management of the increasingly complex task depends on a well developed plan. The plan addresses methods for performing the analysis, definition, evaluation, and decision process; measuring technical performance; and integrating specialty considerations. The plan also relates Systems Engineering to the other activities accomplished by a project team.

Team members at all levels participate in the process. Whether mainstream or support, your participation depends on good documentation and proactive coordination—the vital ingredients for efficiently achieving a totally integrated system.

Additional Information Sources

For further research and understanding, the following sources of information are suggested:

- *Engineering Management,* MIL-STD-499A (USAF)
- *System Engineering and Analysis,* B. C. Blanchard and W. J. Fabrycky, Englewood Cliffs, N.J., Prentice-Hall, 1981
- *Systems Engineering Management Guide,* Defense Systems Management College, Second Edition, December 1986
- *System Engineering Management Plan (SEMP),* DI-S-3618/S-152

Glossary

Concept Development

Concept or system development is done early in a project. It is concerned with the way the system as a whole can satisfy its ultimate purpose, usually within the limits of the resources available. If more than one concept will satisfy the objectives they are then compared, or "traded off."

Configuration Management

Configuration management is the Systems Engineering management process that identifies the functional and physical characteristics of an item during its life cycle. It controls changes to those characteristics, and records and reports change processing and implementation status. One of the more important aspects of configuration management is the establishment and management of the project baseline. Since complex projects are almost always subject to changes during their progress, configuration management ensures that necessary changes are accomplished in a controlled manner.

Constructibility

Constructibility pertains to how practical it is to construct a project. It addresses the capability to transfer design into a capability for efficient production of project objectives. *(See also Producibility)*

Data Management

Data management, as part of Systems Engineering management, refers to collection, organization, and dissemination of information about all system elements. These data include configuration tracking, interface management, equipment and its characteristics, or any other information serving the project team.

Design, Construction, and Startup

These are terms traditional to the engineer/constructor business. In their most successful application they reflect the Systems Engineering or systems management approach, regardless of whether classic systems terminology is used.

Evaluation

Evaluation is a continuing assessment of risk and cost which changes character as the program matures. Initially, it will be tradeoffs between operating requirements and engineering design. As the program moves into development, mathematical modeling and simulations become more predominant. Continuing reviews against criteria such as operability, projectivity, reliability, maintainability, and safety are key to the evaluation process. *(See also System Synthesis)*

Functional Analysis

Functional analysis answers the question, How will it work? The system is analyzed to identify and define interrelated functions that must occur, showing logical sequences and relationships of operational and support functions at the system level.

Interface Management

Interface management is the ongoing task of managing the details at the places where the system elements join. This activity goes hand-in-hand with configuration management and system integration tasks. *(See also Systems Integration)*

Life Cycle Cost

Life cycle cost involves all costs associated with the system (or element) over its life, starting from the research and development phase, to its eventual retirement and deactivation or decommissioning.

Logistics Support

Logistics support is the composite of all considerations necessary to provide a system with all the resources it will need throughout its life. Some of the elements of logistics support are maintenance planning, supply support, test and support equipment, personnel and training, technical manuals, facilities, and provisioning for spares.

Maintainability

Maintainability is a design characteristic dealing with the ease, speed, safety, and economy of keeping a system operating in the proper manner.

Operability

Operability (operational capability) measures the effectiveness of actual system operation in terms of its purpose or mission. Important aspects of a system's operability are system effectiveness, operational readiness, availability, reliability, frequency of repair, mean time between failure, and amount of down time.

Producibility

Producibility pertains to how practical it is to produce a product. It addresses the capability to transfer design into the capability for efficient production of project objectives. *(See also Constructibility)*

Reliability

Reliability is the probability that a system or product will perform in a satisfactory manner for a given period of time, when used under specified operating conditions.

Requirements Analysis

The requirements analysis process lays the groundwork for actually implementing the project. This process is comprised of three essential parts: functional analysis, trade studies, and synthesis. Requirements are developed well enough so that real resources can be safely committed.

Risk Analysis

Risk analysis is an analytical process of determining what can realistically go wrong in a system, what the adverse consequences can be, and how the consequences may be mitigated.

System

A system is a group of interacting personnel, procedures, items, devices, ideas, elements, and subsystems joined as a whole to serve a common purpose or objective.

Systems Integration

Systems integration makes all the elements of a project work together in a manner consistent with its ultimate purpose. Within a complex system these elements can include tangible items such as hardware, and intangibles such as reliability and productivity. Systems integration can also concern itself with the ways several organizations work together on the same project.

System Safety

System safety refers to designing safety into the system so that the subsystems and elements work individually and collectively. This effort assumes that the safety of the process, environment, and personnel will not be compromised under normal and abnormal conditions that were predefined and agreed to.

System Synthesis

This is the step where the selected concept is evaluated within the environment that it must perform. System synthesis is a modeling or simulation activity that provides the "how to" for the functions defined in the functional analysis. It can start with a simple block diagram and go to finer detail with physical and mathematical modeling. This phase aids in the development of the system test, support, and operational requirements. *(See also Evaluation)*

Test, Validation, and Operating Services

These are services generally offered during the latter phases of a project. Testing is conducted to see if the project or system performs as needed, and validation is performed to prove that the test results are sufficient to guarantee this performance. Operating services consist of doing everything necessary to efficiently run the project or system for the client.

Tradeoff Studies

Tradeoff studies compare and select the "better" of the available alternatives. The best one may not be found—leading to a decision to try out and test the leading candidates. Desirable and practical tradeoffs can be made between operational needs, engineering design, project schedule and budget, constructibility/producibility, and life cycle costs, as appropriate. Tradeoffs are continually identified and assessed.